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**The Thesis Committee for Adam Ray Bowerman  
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**A Southern Hemispheric influence on the North Atlantic through a  
shallow atmospheric circulation response**

**APPROVED BY  
SUPERVISING COMMITTEE:**

**Supervisor:**

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Rong Fu

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Robert Dickinson

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Zong-Liang Yang

**A Southern Hemispheric influence on the North Atlantic through a  
shallow atmospheric circulation response**

**by**

**Adam Ray Bowerman, B.S.Geo.Sci.**

**Thesis**

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## **Dedication**

This work is dedicated to the family that I was born to and the family that I have chosen, whose continued support has buoyed my academic accomplishments. I would like to give special dedication to my son, Adam, without whom I would still be lost.

## **Acknowledgements**

I would like to give very special thanks to Dr. Rong Fu. Without your guidance, patience, and friendship I would never have discovered my new view of the natural world. Also, thank you to my committee members, Dr. Robert E. Dickinson and Dr. Liang Yang, and my research group. Your teachings and questions have sharpened my mind and given me the tools necessary for deep scientific exploration. The Jackson School of Geosciences deserves abundant praise for their unwavering support during my journey here.

## **Abstract**

### **A Southern Hemispheric influence on the North Atlantic through a shallow atmospheric circulation response**

Adam Ray Bowerman, M.S.Geo.Sci.

The University of Texas at Austin, 2016

Supervisor: Rong Fu

Previous research has discussed the importance of meridional migrations of the North Atlantic Subtropical High (NASH) on U.S. precipitation patterns, but the mechanisms that control these meridional migrations are virtually unknown. We have observed that, under certain conditions, a southward migration of the NASH is associated with deep tropical incursions of cold surges from the winter hemisphere over South America. When upper tropospheric winds are westerly over Amazonia, cold surges originating from extratropical South America can penetrate deep into the tropics and increase geopotential height over a broad region span from equatorial South America, across the intra-American seas, and into the subtropics of the Northern Atlantic, with anomalies exceeding +1 standard deviation to at least 18°N. The anomalous geopotential and temperature gradients associated with the South American cold surge induces a shallow tropical meridional circulation. The latter in turn increases the lower tropospheric geopotential height over the tropical to subtropical North Atlantic, leading to the

equatorward expansion of the NASH. This study uncovers the importance of shallow circulations in the cross-equatorial teleconnection.

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# **A Southern Hemispheric influence on the North Atlantic through a shallow atmospheric circulation response**

## **Introduction**

The body of work on the mechanisms that control the cross equatorial flow and teleconnections between hemispheres is relatively small, especially over the American-Atlantic sector. Thus, any new findings can contribute significantly to this small body of the literature. My thesis characterizes the influence of South American winter cold surges on the low-level interhemispheric flow and variability in the southern boundary latitude of the summer North Atlantic Subtropical High (NASH). The results indicate significant lower atmospheric variability throughout the Intra-Americas region and may possibly be extended to other regional circulation features of the Northern Hemisphere tropics and subtropics.

The geology of the Intra-Americas region offers a unique setting for the study of atmospheric interactions between the Northern and Southern Hemispheres. The Andes Mountains extend the length of South America, crossing into the Northern Hemisphere as the southernmost chain of the American Cordillera. In the lower and middle troposphere, the mechanical block leads to lee troughs that can extend deep into the tropics, and low-level jets that feed the lee cyclogenesis with moisture transported from humid western Amazonia. In the upper-troposphere, weak westerly wind enables equatorward propagation of short planetary waves stemming from Pacific-South American wave trains (Kleeman et al. 1989; Marengo et al. 2002).

Previously described equatorially propagating planetary waves over South America (Garreaud; Wallace 1998; Li; Fu 2006; Liebmann et al. 2009; Lupo et al. 2001; Marengo et al. 1997; Parmenter 1976; Pezza; Ambrizzi 2005; Vera; Vigliarolo 2000) suggest the possibility that an upper level interhemispheric teleconnection may exist, so long as the upper level tropical wind conditions are favorable. Cross equatorial wave propagation had been detected in observations (Newell et al. 1969) previously in certain regions globally, but could not be theoretically explained until the works of Charney (Charney 1963, 1969) and Dickinson (Dickinson 1970) outlined the theoretical framework concerning the interactions of midlatitude planetary waves with the tropical atmosphere. The works of Charney and Dickinson were later expounded upon, establishing the idea of the “westerly duct” (Webster; Holton 1982). The westerly duct is a region of weak upper level westerly flow in the tropical atmosphere embedded in a mean easterly basic state, and allows planetary waves with a zonal scale less than that of the region of weak westerlies to propagate into the opposite hemisphere. The eastern Pacific is a region where westerly ducts are commonly detected, but other regions, such as the eastern Atlantic, also show evidence for this phenomenon (Tomas; Webster 1994).

Over Amazonia tropically incurring planetary waves are sometimes accompanied by low-level cold surges throughout the year, but are most common over South America in austral winter (Lupo et al. 2001). Strong winter cold surges can inject cool, dry air deep into the tropical low-level atmosphere. Although the influence of such cold surges on rainfall and surface temperature over Amazonia have been studied (Garraud and Wallace

1998; Li and Fu 2006), whether their influence can reach beyond southern hemisphere South America has not been investigated.

Love (1985a,1985b) demonstrated that the low level signal from Asian and Australian cold surges could influence the tropical circulation of the opposite hemisphere. He noted that in a few cases, a cyclonic, low-level shear zone would be created in the opposite hemisphere with the potential to spin up tropical cyclone activity. These works are the only studies to my knowledge that show the inter-hemispheric influence of cold surges.

The NASH is one of two major Northern Hemisphere oceanic subtropical anticyclones, and is a semi-permanent feature of the low-level North Atlantic subtropics. The climatological core of the NASH is anchored over the central and eastern North Atlantic, but the NASH exhibits substantial variability in both intensity and morphology at daily, interannual, and decadal time scales. The NASH reaches its greatest strength during the boreal summer months, the period of the most concern in this paper, and is often called the “Bermuda High” because of the frequent westward expansion of the core region from its climatological position over the Azores islands to the western North Atlantic over Bermuda.

The oceanic subtropical anticyclones were once assumed to arise from overturning and subtropical descent due to tropical convection, the so called “Hadley Cell” model. However, it was found that the summer hemisphere the Hadley Cell could be weak or even non-existent (Lindzen; Hou 1988), implying that tropically induced overturning could not explain the strong subtropical anticyclones over the ocean basins. Since this finding, many

competing hypotheses have been suggested to describe the mechanisms that create and sustain the subtropical anticyclones. Some of these hypotheses invoke remote interactions with monsoon dynamics (Chen et al. 2001; Rodwell; Hoskins 2001), localized diabatic processes (Liu et al. 2004; Miyasaka; Nakamura 2005), or some combination of the two (Seager et al. 2003).

Chen et al. (2000) argued that the oceanic subtropical anticyclones over the Pacific and Atlantic arise from zonally asymmetrical subtropical heating patterns forced by the Asian Monsoon. They viewed the North Pacific Subtropical High (NPSH) and the NASH as stationary Rossby waves resulting from the eastward propagation of energy from an Asian heat source. Rodwell and Hoskins (2001) adapted the monsoon-desert hypothesis (Rodwell; Hoskins 1996) to explain the oceanic subtropical anticyclones, invoking a Gill-type response to upper level monsoonal heating over Asia and North America. Latent heating interacts with the upper level westerly winds to produce cold advection and descent to the west of the monsoon, which is then orographically enhanced to form the subtropical anticyclones. This “upstream” influence is in contrast to the “downstream” mechanism put forth by Chen et al. (2000).

To explain the variable western flank of the subtropical anticyclones, Rodwell and Hoskins (2001) argued that a moisture return flow into the monsoon region is necessary to restore Sverdrup balance, using as an example the low-level jet system flowing along the western ridge of the NASH. To explain the variability of the southern NASH ridge they invoke a tropical response to easterly Kelvin waves, but provide no other elaboration for their hypothesis. Though subsequent studies would challenge and elaborate upon these

findings, Rodwell and Hoskins (2001) highlights the quasi-independent nature of the mechanisms influencing the eastern, western, and southern portions of the NASH.

As more work was devoted to the study of the subtropical anticyclones, it became clear that local diabatic enhancement was necessary to explain the strength of the summer anticyclones. Modelling studies conducted by Seager et al. (2002) agreed with the fundamental findings of Rodwell and Hoskins (2001), but noted that if only the dynamical forcing from monsoonal heating is considered, the anticyclonic response produced over the ocean is weak. They noted that differential diabatic heating and atmospheric interaction with ocean currents must play an important role in the strengthening of the NASH to its observed magnitude.

Liu et al. (2003) provide a subtly contrasting argument to those previously presenting. They propose that monsoonal heating and dynamically induced descent is not necessary for the formation of the subtropical anticyclones, and that they can instead be initiated by column diabatic heating contrasts between continent and ocean. Their “LoSeCoD” hypothesis still highlights the quasi-independent forcing mechanisms for the eastern and western portions of the subtropical anticyclones. Liu et al. (2003) argues that the eastern core of the anticyclones are generated by a low level contrast between longwave cooling over the eastern ocean basin (producing anticyclonic rotation) and sensible heating over the western continent (producing cyclonic rotation), while the western portion of the anticyclones are a response to latent heating over the eastern continent and a “double dominant” diabatic heating over the western ocean. Though this work arrives at a more fundamental mechanistic view for the existence of the subtropical anticyclones, the

diabatic heating contrasts do not arise on their own, but are generated by land-ocean-atmosphere processes such as monsoons, ocean currents, and clouds.

With findings congruent with Liu et al. (2003), Miyasaka and Nakamura (2005) also examined the three-dimensional structure of the subtropical anticyclones, finding that the diabatic heating contrasts between ocean and continent were necessary for the subtropical anticyclones to achieve their observed strength. They note that the subtropical anticyclones are not sensitive to the domain size or position of the monsoonal heating so long as the diabatic heating contrasts are present, but that the monsoon circulation could enhance these local diabatic factors (sensible heating, longwave cooling, etc.). In contrast with the mechanism presented by Chen et al. (2000), it is found that the NPSH is not impacted by downstream propagation of Rossby waves from the Asian Monsoon, but that the NPSH is actually a source for Rossby waves that then propagate eastward and impact the NASH.

Many of the more recent studies regarding the NASH have focused on variability, particularly the boreal summer expansion of the western NASH ridge into the western North Atlantic and Gulf of Mexico. The interannual expansion and contraction of the western NASH ridge has profound impacts on the Intra-Americas circulation, including the routing of low-level moisture into North America (Li et al. 2011a; Li et al. 2013; Li et al. 2011b) and influencing the timing of the demise of the North American monsoon (Arias et al. 2012). In addition, the westward expansion of the NASH can trigger severe midsummer droughts across the Intra-Americas (Kelly; Mapes 2011, 2013) and may have influence over the routing of North Atlantic tropical cyclones (Wang; Lee 2007).

Li et al. (2011) examined the influence of westward expansion of the NASH ridge and NASH intensity on precipitation over the eastern U.S., and found that since 1978, the NASH western ridge has shown a decadal scale expansion and enhancement of the north-south displacement of the western ridge. They note that other factors besides NASH intensity need to be considered to explain the variations in western NASH expansion and its meridional migration. Their subsequent work (Li et al. 2012) builds upon this knowledge by detailing the NASH “ridging types” (e.g. NW ridging, SW ridging, etc.) and highlighting their relationship with the NASH core intensification, the link to the Pacific Decadal Oscillation, and anthropogenically induced climate change.

Kelly and Mapes (2011) used a zonal momentum budget decomposition to demonstrate that increased easterlies in the North Atlantic subtropics, western North Atlantic precipitation deficits, and NASH westward expansion are related to variability of the Indian Monsoon. They noted that with increased monsoonal heating and intensification of the Tibetan High, the divergence of eddy momentum flux can accelerate the column zonal mean easterlies of the subtropics across Africa and into the North Atlantic. The increase of the subtropical easterlies contributes to the westward expansion of the NASH and increased stability in the western North Atlantic.

Most previous works are focused either on the creation and sustainment of the NASH core or mechanisms for western expansion of the NASH, but a few papers have highlighted the importance of meridional structure and variability of the southern NASH ridge. As previously stated, Rodwell and Hoskins (2001) describe the southern NASH ridge as a response to easterly Kelvin waves propagating through the tropics. The NASH

has also been shown to have a non-homogeneous vertical structure (Miyasaka; Nakamura 2005), with a baroclinic structure along its southern flank where the low-level easterlies accelerate, and a barotropic structure over much of the rest of the NASH region. Li et al. 2012 attribute the equatorward migration to a strengthening of the NASH core.

The objective of this paper is to explore whether the cold surges originating from extratropical South America can influence northern hemispheric South America, the Intra-American sea, and the tropical and subtropical North Atlantic, especially the meridional displacement of the NASH's southern boundary. My results suggest a teleconnection pathway whereby South American winter cold surges can impact the circulation of the Northern Hemisphere tropics and subtropics by influencing the low-level cross equatorial flow over Amazonia and induce an equatorial migration of the NASH. The data and methods used are detailed in Section II, the results and figures are described in Section III, and a summation and discussion of the mechanism and its broader impacts are given in Section IV.



## **Data and Methods**

For this study, the Modern-Era Retrospective Analysis for Research and Applications (MERRA) (Rienecker et al. 2011), supplied by the Global Modelling and Assimilation Office, is used. This reanalysis product is averaged into daily fields on a global  $1.25^{\circ}$  latitude x  $1.25^{\circ}$  longitude grid over the time period from 1979 to 2013. The variables employed in this study are geopotential height, temperature, horizontal wind, and vertical velocity. Some noted issues with the MERRA reanalysis product include shallower atmospheric diabatic heating over the South American sector, leading to lower bias in the tropical upper tropospheric diabatic heating compared to other re-analyses (Wright et al. 2013), and the dehydration processes in the tropical tropopause layer due to representations of equatorially trapped wave modes (Fujiwara et al. 2012). These issues could in principle underestimate the deep circulation response to convective heating over tropical South America, potentially weakening the response of the Northern Hemispheric circulation to southern hemispheric forcing. I am in the process of repeating the analyses reported here using the European Center for Medium-Range Weather Forecast (ECMWF) Reanalysis (ERA)- Interim, to determine if the results are robust across reanalyses.

To demonstrate the presence of convective activity associated with the leading edge of cold surges, the National Oceanic and Atmospheric Administration (NOAA) interpolated Outgoing Longwave Radiation (OLR, Liebmann; Smith 1996) data set is used. This data set is derived from the compilation of data from 10 NOAA satellites

over the period from 1979 – 2013 which is then temporally and spatially interpolated onto a  $2.5^\circ$  latitude x  $2.5^\circ$  longitude global grid.

Composite analysis is used extensively here, with conditions based upon the cross-equatorial meridional wind over Amazonia, referred to as the South American Monsoon V-index, because of its strong correlation with geographic rainfall distribution over Amazonia (Wang; Fu 2002), and the presence of upper level tropical westerlies over the same region. The specific conditions and their rationale for compositing are explained further in the next section. Local significance testing is measured by the z-test and further verified by Monte Carlo simulation, while field significance is determined through the Walker test (Wilks 2006).

## Results

Most of the daily atmospheric fields used for lead-lag compositing are taken from the MERRA reanalysis and include geopotential height, horizontal wind, pressure velocity, and air temperature, with the inclusion of the NOAA interpolated OLR as a proxy for cloud cover. The JJA time means (1979 - 2013) of these atmospheric fields are shown in Figure 2 for 850 hPa (top panels), 200 hPa (middle panels), and a pressure-latitude plot averaged along longitudes that run through the central South American and the NASH regions ( $57.5^{\circ}\text{W} - 62.5^{\circ}\text{W}$ ).

The climatological domain of the NASH at 850 hPa is apparent in Figure 1b as a peak in geopotential height in the North Atlantic, and its geostrophic impact on the acceleration of the subtropical easterlies along its southern flank and the southerlies that carry moisture into central North America can be clearly seen. The OLR climatology for JJA (Figure 1a) shows the lowest values, or deepest convection, occurring just north of the equator over ocean and spreading into the North American Monsoon region and Northern Hemispheric South America. Of particular note is the weak northeasterly or easterly wind at the 200 hPa in the equatorial South America and Atlantic ( $5^{\circ}\text{S}-5^{\circ}\text{N}$ ), and weak westerlies between  $5^{\circ}\text{S}-10^{\circ}\text{S}$  over South America (Figure 1d). Such upper-level zonal wind distribution can favor the equatorward propagation of the planetary waves associated with cold surges deep into the tropical South America, but not across the equator. The vertical-latitudinal cross-section in Figure 1e shows that the atmospheric circulation stemming from

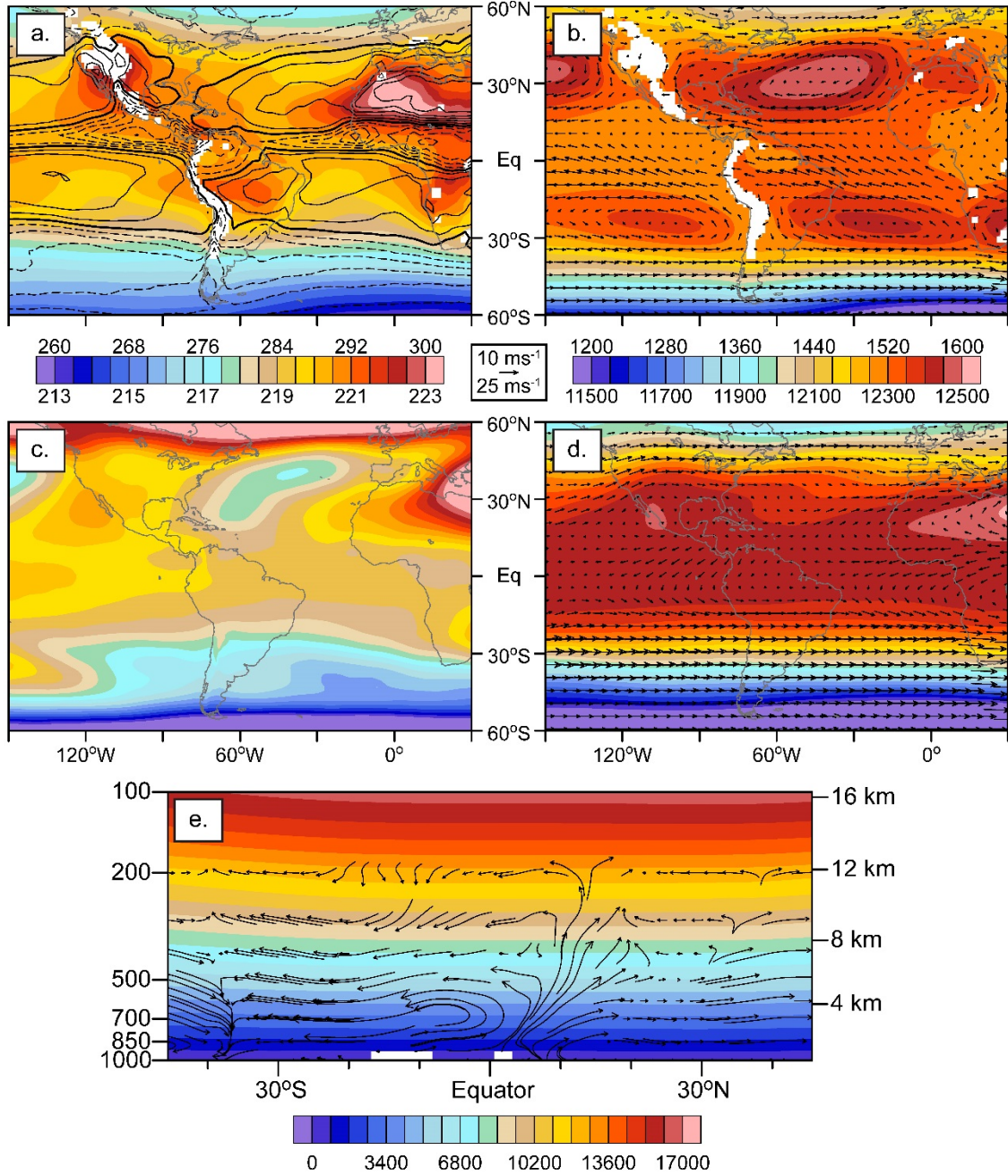


Figure 1: Climatology (1979-2013) for [a.] 850 hPa air temperature (shading) and top of atmosphere OLR (contours), where the 250 Wm<sup>-2</sup> contour is bolded and values above (below) 250 Wm<sup>-2</sup> are plotted as solid (dashed) contours at 10 Wm<sup>-2</sup> intervals. [b.] Climatology for 850 hPa geopotential height (shading) and 850 hPa horizontal wind (vectors). [c.,d.] Same as [a.,b.], respectively, except for 200 hPa fields and no OLR contours in [c.]. [e.] Climatology from 45°S to 45°N, averaged over the 62.5°W to 57.5°W domain, for column geopotential height (shading) and column meridional circulation (curly vectors).

the areas of tropical convection consists of not only a deep tropospheric component, but also has a shallow meridional circulation (SMC) that overturns in the middle atmosphere (Nolan et al. 2007).

We first inspect potential sources of the daily variation of the NASH. We begin by visually inspecting various atmospheric fields on days before, during, and after equatorward migrations of the NASH southern boundary below  $16.5^{\circ}\text{N}$  (70 total events). Three main atmospheric patterns emerge from this analysis. The first is a low-level high pressure anomaly propagating along the subtropical easterlies from Africa and across the North Atlantic, reminiscent of the mechanism for NASH westward extension described in Kelly and Mapes (2011/2013). The second atmospheric pattern seen during NASH equatorward migration involves a strengthening of the NASH core region as described by Li et al. (2011/2012), possibly in response to Northern Hemisphere midlatitude influence. The third pattern bears no resemblance to previously described mechanisms and involves 23 of the 70 total events (33%), showing an interhemispheric pattern resembling South American cold surges that appear to influence the low-level cross equatorial flow over Amazonia and then extend into the Northern Hemisphere subtropics. It is this interhemispheric mechanism which will be investigated further.

To investigate possible interhemispheric influence on the NASH southern boundary variations suggested by the third pattern discussed above, we evaluate a composite of the circulation anomalies before and after variations of the cross-equatorial flow over South America, represented by the V-index. The V-index is calculated as the area averaged daily meridional wind at 925hPa over the domain of  $5^{\circ}\text{N} - 5^{\circ}\text{S}$ ,  $65^{\circ}\text{W} -$

75°W, Wang and Fu 2000). Utilizing the V-index as a basis for compositing of atmospheric variables is cleaner and computationally simpler than identifying South American cold surges by previously described methods (Lupo et al. 2001; Pezza; Ambrizzi 2005), and then selecting those cold surges that reach the deep tropics. In addition, the interhemispheric flow that the V-index represents lies spatially between the cold surges and the NASH, and allows the interhemispheric pathway to be isolated and tested independently.

In this study a lead-lag compositing method is used extensively to show changes in the previously described atmospheric fields over the days before, during, and after large positive V-index events. We have tested the composite based on the days when the southerly V-index is greater than its  $+2\sigma$  value. Though the resulting composites resembled South American cold surge events in the Southern Hemisphere, the impact did not extend deep into the Northern Hemisphere tropics and subtropics. However, we found that when the southerly V-index is greater than its  $+2\sigma$  value, and the upper level wind over Amazonia ( $15^{\circ}\text{S} - 0^{\circ}$ ,  $50^{\circ}\text{W} - 70^{\circ}\text{W}$ ) is westerly and greater than  $2\text{ms}^{-1}$ , there are significant variations in the 850 hPa geopotential height over the Northern Hemisphere subtropics associated with the cold surge. Conversely, if easterly zonal wind anomalies were present during the events when the southerly V-index is greater than its  $+2\sigma$  value, there are no significant variations in the 850 hPa geopotential height over the Northern Hemisphere subtropics associated with the cold surges..

Thus, we analyze the composite geopotential height, horizontal wind anomalies, and normalized (by local standard deviation) geopotential height and temperature

anomalies at 850 hPa, as well as the OLR anomalies before, during and after the days when the southerly V-index is greater than its  $+2\sigma$  value and Southern Hemisphere 200 hPa averaged tropical ( $10^{\circ}\text{S} - 0, 57.5^{\circ}\text{W} - 62.5^{\circ}\text{W}$ ) zonal winds are equal to or greater than  $+2\text{ms}^{-1}$ . If the southerly V-index is greater than its  $2\sigma$  value on consecutive days, only the first day was chosen for the composite. Choosing the  $+2\text{ms}^{-1}$  200 hPa zonal wind condition was not an arbitrary decision, because of the 55 original composite members based on the V-index alone, only two had 200 hPa wind values that fell between  $\pm 2\text{ms}^{-1}$ , with thirty members above  $+2\text{ms}^{-1}$ , and twenty-three members below  $-2\text{ms}^{-1}$ . The resulting lead-lag composites for the days before, during, and after the composite conditions are met are shown in Figure 2, with only locally significant values shown for horizontal wind and standardized temperature and geopotential height. If  $+5\text{ms}^{-1}$  is used as the upper level tropical wind condition, number of composite members is reduced and the 850 hPa geopotential height anomalies over the Northern Hemisphere are stronger (not shown), highlighting the importance of the direction and magnitude of upper level winds to the low level teleconnection.

Two days before a  $+2\sigma$  V-index event (Day -2) the southern boundary of the NASH, shown as the bold geopotential (1560 gpm) contour is within one standard deviation of the seasonal variability. On the windward side of the midlatitude Andes, high pressure has already built up and is beginning to cross to the leeward side as a cold surge over Argentina. The first hints of a frontal system can be detected in the anomalous OLR, with low OLR anomalies near the Altiplano region and high OLR anomalies straddling the southern Andes.

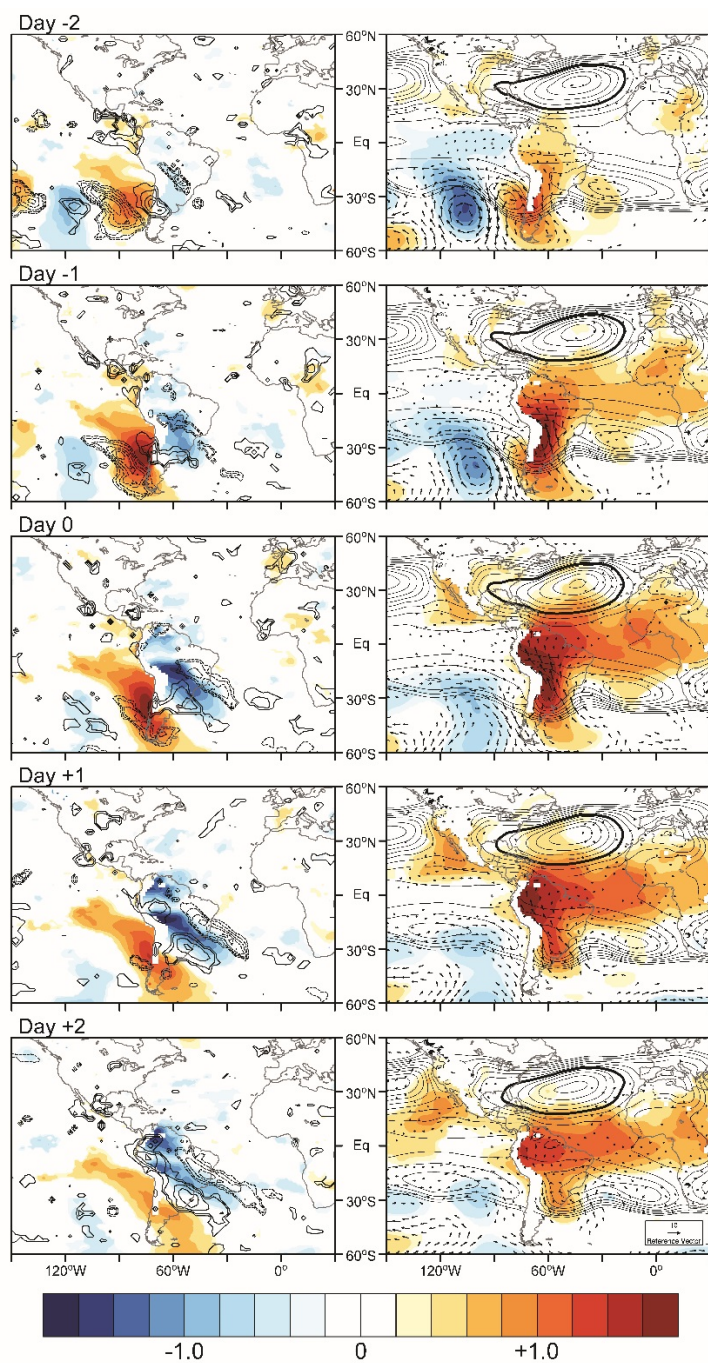


Figure 2: Daily lead-lag map composites based on  $+2\sigma$  V-index events at Day 0 with equatorial 200 hPa zonal wind anomalies greater than  $+2\text{ms}^{-1}$ . Left column displays TOA OLR anomalies (contours) and standardized 850 hPa air temperature anomalies (shading). Right column displays 850 hPa geopotential height (contours) from 1500 – 1610 gpm with the NASH boundary (1560 gpm) bolded, 850 hPa horizontal wind anomalies (vectors), and standardized 850 hPa geopotential height anomalies (shading). Only anomalous values that are locally significant at 95% confidence are shown.



By Day -1 the change in 850 hPa geopotential over central South America has exceeded  $+1\sigma$  and temperatures begin to drop in the midcontinent as the cold surge advects equatorward. The isobars in the low level tropical atmosphere in both hemispheres begin to migrate equatorward as tropical pressure increases. Note that as the tropical atmosphere is visibly affected, the latitude of the NASH boundary has changed little.

At Day 0, the day that the described composite conditions are met, the geopotential anomalies associated with the cold surge have increased to greater than  $+1\sigma$  across the entirety of the South American continent and into the subtropics of the Northern Hemisphere, with geopotential anomalies over the Altiplano exceeding  $+1.5\sigma$ . The NASH boundary has visibly migrated equatorward (for comparison, see Figure 3) in response to the increase of geopotential exceeding  $+1\sigma$  over the tropical and subtropical Atlantic Ocean, coinciding with strong southerly tropical wind anomalies associated with the cold surge coming from the Southern Hemisphere. Over subtropical South America, OLR anomalies develop that are indicative of a frontal system along the leading edge of the cold surge, with colder temperatures being advected northeastward with the front. Also note that over Northern Hemisphere South America, temperatures have cooled by  $1\sigma$ , suggesting that the cold surge that comes from the Southern Hemisphere midlatitudes has advected deep into the tropics and crossed hemispheres.

On Day +1, cold anomalies continue to develop along the axis of the frontal system and tropical temperatures over Northern Hemisphere South America drop by over  $1.5\sigma$ . Geopotential height anomalies also exceed  $+1.5\sigma$  in the tropics, and it should be noted that this sets up both an anomalous temperature and geopotential gradient between Northern

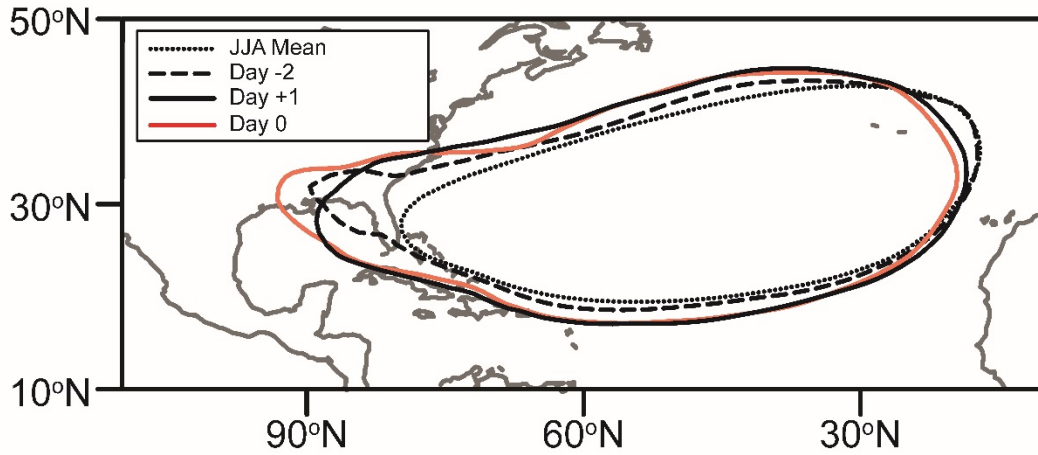


Figure 3: Overlay plot of the NASH boundary (1560 gpm contour at 850 hPa) for Day -2 (dashed black line), Day 0 (red line), Day +1 (solid black line), and the JJA mean (gray dotted line). The Day -2, Day 0, and Day +1 contours are taken from Figure 2.

Hemisphere South America and the warmer waters of the adjacent Intra-Americas sea to the north. In response to the sustained geopotential height anomalies, the NASH boundary retains its equatorward expansion with the western ridge changing character from the “northern ridging type” to the “southern ridging type” described in Li et al. (2011/2013). The geopotential anomalies along the NASH southern boundary still exceed  $+1\sigma$ .

The NASH southern boundary begins to retreat equatorward on Day +2 as the geopotential and horizontal wind anomalies weaken in the tropics and Northern Hemisphere subtropics. Cold anomalies weaken along the frontal system axis as the front extends into the tropics, but still remain colder than  $-1.5\sigma$  in parts of Northern Hemisphere South America. Though the NASH southern boundary begins retreating poleward, it is still not as far north as that on Day -2.

To highlight the significance of the equatorward expansion of the NASH seen in Figure 2, the mean JJA NASH position is compared to the composite NASH boundaries at Day -

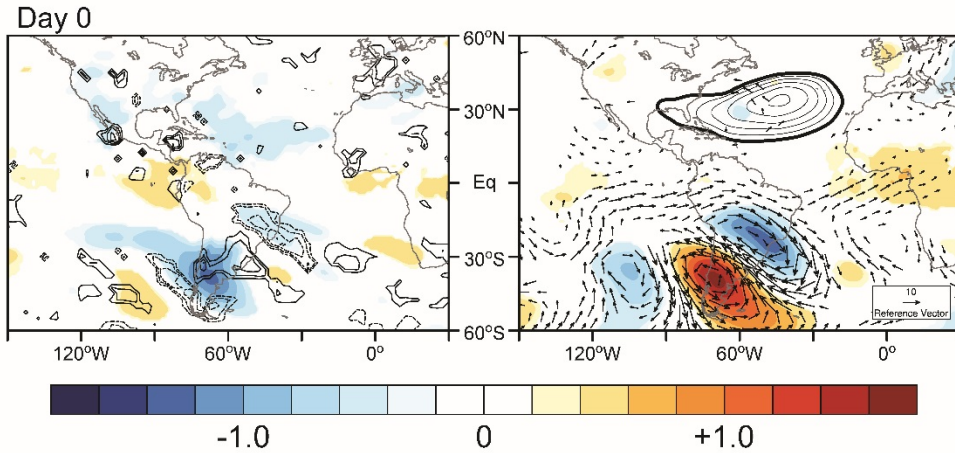


Figure 4: Same as Figure 2 except 200 hPa anomalous fields are shown for Day 0 only, with geopotential height contours in the right panel shown for the NASH domain only (1560 – 1600 gpm at 850 hPa).

2, Day 0 and Day +1 (Figure 3). The Day -2 NASH position falls within  $1\sigma$  of the JJA averaged NASH position, however the Day +1 composited NASH boundary is expanded by greater than  $2\sigma$  over the JJA NASH position, representing a significant change in NASH morphology. The  $2\sigma$  equatorward expansion of the southern NASH boundary, together with the significant positive geopotential anomalies exceeding  $+1\sigma$  along the southern NASH boundary and stronger than  $+2\sigma$  increases of the southerly low-level cross-equatorial flow during and after South American cold surges, suggest a potentially significant influence of the latter on lower tropospheric circulation over the North Hemispheric Atlantic Ocean, especially the southern part of the NASH.

Figure 4 shows the composite anomalous 200 hPa horizontal wind, standardized temperature, and standardized geopotential height for the same events as in figures 3 and 4. For brevity, only composites for Day 0 are shown. The 200 hPa composites clearly show in the horizontal wind and standardized geopotential height the associated wave

pattern emanating from the South Pacific that accompanies South American cold surges. Also evident in the horizontal wind anomalies are the increased tropical westerlies, stretching from the Eastern Pacific, over South America, and into the tropical Atlantic, creating conditions conducive to deep penetration of midlatitude planetary waves into the tropics. However, the anomalous 200hPa geopotential height shows that the wave pattern does not propagate across the equator into the Northern Hemisphere, indicating that the change in the NASH southern boundary is not a result of cross-equatorial planetary wave propagation.

Using the same compositing method as for Figure 2, Figure 5 shows a meridional-height cross-section of the troposphere ranging from 45°S – 45°N and averaged from 57.5°W – 62.5°W for the days before, during, and after composite conditions are met. The fields displayed are normalized geopotential height and the meridional circulation through the depth of the troposphere, with only locally significant values shown. For normalized geopotential height, values exceeding  $+1\sigma$  are outlined by the dashed white contour.

On Day -2 a southerly wind extending the depth of the troposphere is evident in the Southern Hemisphere subtropics and is indicative of a South American cold surge. The negative geopotential anomalies centered at 20°S in the upper levels correspond to the mid-continental trough over South America displayed in Figure 4. Weak, positive low-level geopotential anomalies are already developing across the South American continent and into the Northern Hemisphere as the cold surge begins.

The southerly wind strengthens with the advancing cold surge on Day -1, and Southern

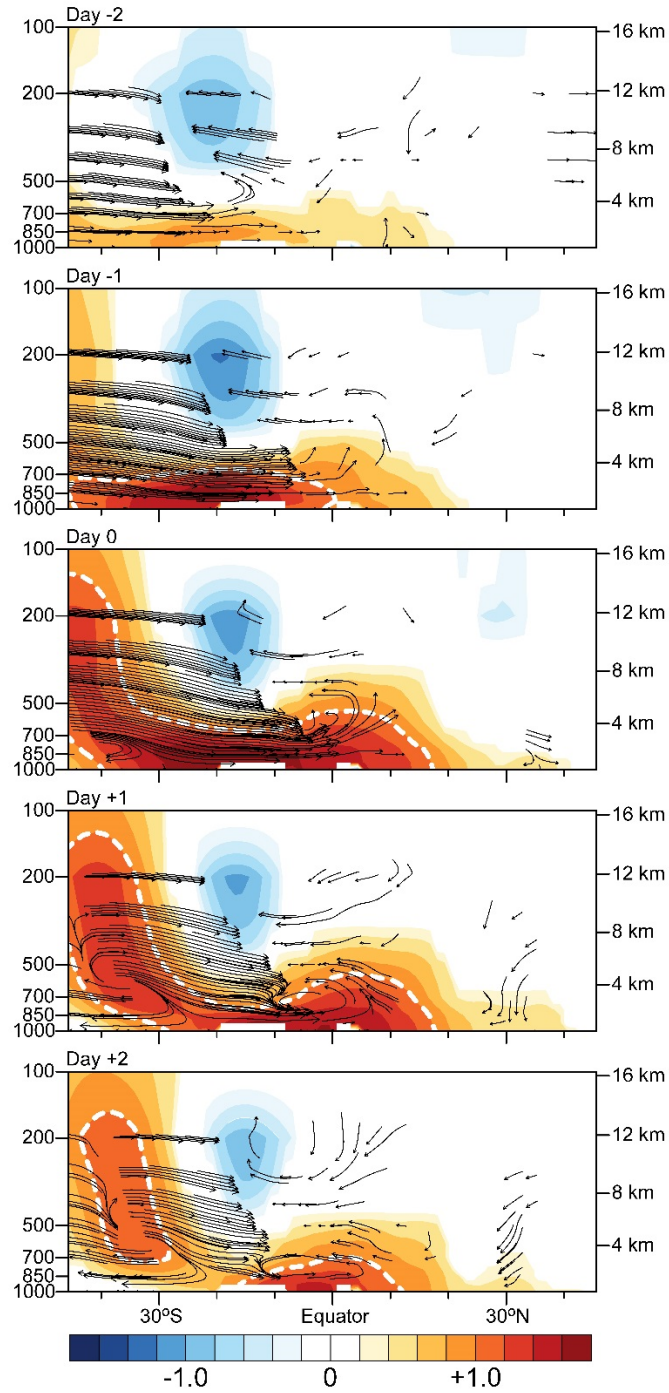


Figure 5: Daily lead-lag pressure-latitude composites averaged from 62.5°W to 57.5°W based the same conditions as Figure 2. Fields displayed are standardized column geopotential height anomalies (shading) with the  $+1\sigma$  contour denoted by the white dashed line, and column meridional and vertical wind anomalies (curly vectors). Only locally significant values at 95% confidence are shown for each field.

Hemisphere geopotential height anomalies over South America begin to exceed  $+1\sigma$  in the lower troposphere from the mid-latitudes to the tropics, due to cold temperature advection by the cold surge. Also note that any wind or geopotential height anomalies present in the Northern Hemisphere are very weak. As the anomalous geopotential height gradient is increased in the tropical Northern Hemisphere, an anomalous shallow meridional circulation (SMC) in the lower troposphere begins to form, with an upward branch at about  $10^\circ\text{N}$  and return flow to the Southern Hemisphere in the middle troposphere.

By Day 0 the cold surge advances into the deep tropics in the low level atmosphere, and a tongue of increased geopotential height follows, with anomalies exceeding  $+1\sigma$  extending into the Northern Hemisphere subtropics. The strong Northern Hemisphere subtropical geopotential height anomalies are timed with equatorward migration of the NASH southern boundary shown in Figure 2 and Figure 3. Cooling over the Northern Hemisphere portion of South America and a strong meridional geopotential height gradient set up by the cold surge create conditions conducive to the development of a SMC in the lower and middle tropical troposphere, with low-level winds flowing northward and a southward return flow at about  $5^\circ\text{N}$  between 700 and 500 hPa, presumably in responding to the anomalously low geopotential center in the middle and upper troposphere over the tropical southern hemisphere.

Recalling from Figure 2 (Day +1), the NASH remains equatorially extended and the NASH western boundary takes on a “southwest ridging” character, as defined in Li et al. (2014). These events happen as the SMC is strengthened at Day +1 with anomalous divergence occurring at  $10^\circ\text{N}$  -  $15^\circ\text{N}$  in response to the SMC overturning. The low-level

tongue of  $+1\sigma$  geopotential height anomalies remains in the Northern Hemisphere subtropics as the NASH is equatorially extended, and anomalous subsidence can be detected in the NASH core region at  $30^\circ\text{N}$ , presumably in response to colder near surface temperature and divergence in the Northern Hemisphere subtropics.

By Day +2 the low-level geopotential anomalies and SMC weaken as the cold surge weakens. However, geopotential height anomalies greater than  $+1\sigma$  can still be detected as far as  $11^\circ\text{N}$  with significant anomalies of lower magnitude into the subtropics. The timing of the weakening of anomalous geopotential height occurs simultaneously with the first signs of contraction of the NASH southern boundary seen in Figure 2 (Day +2).

The analyses shown in figures 3-6 suggest that the increase of 850 hPa geopotential height, the southward expansion (and perhaps strengthening) of the NASH, and strong increase of southerly low-level cross-equatorial flow over the South America are linked by an anomalous SMC shown in Figure 5.

## Discussion and Conclusions

Not every South American cold surge penetrates so deeply into the tropics, but those that occurred in the presence of the upper level westerlies can penetrate deeper into tropical South America. The tropically incurring surge increases the northward gradients of low-level geopotential height and temperature that enhances southerly cross-equatorial flow in the lower troposphere over South America. The anomalous low geopotential high center in the middle to upper troposphere over southern hemispheric tropical South America, due to the increase of convection along the leading edge of the cold front (e.g., Garreaud; Wallace 1998; Li Fu 2006), increases the southward geopotential gradient, presumably driving the northerly return flow in the middle troposphere (700 – 500 hPa). Such opposite meridional pressure gradients between the lower and middle troposphere, driven by cold fronts originated from the southern hemisphere extratropics, probably drives the anomalous meridional shallow circulation that spans from the southern to the northern hemisphere. Since upper tropospheric variability in the northern hemisphere is insignificant, it does not appear to play a direct role in the increase of subtropical geopotential height in the lower troposphere over the Northern Hemisphere during these events. Thus, the increase of lower tropospheric geopotential height in the tropical and subtropical North Atlantic and the resultant equatorward migration of the NASH southern boundary, must be a consequence of the anomalous SMC driven by Southern Hemisphere cold surges.

Westward expansion of the NASH has previously been attributed to diabatic heating contrasts between continental North America and the western North Atlantic, variability of



the North American Monsoon, and eddy momentum flux divergence from the Tibetan High. However, only a small body of work has been devoted to describing mechanisms for the meridional migrations of the NASH. These meridional migrations have been previously described as north-south “ridging types” of the NASH western boundary, shown to occur when the NASH core is strengthened and the boundaries expand as a consequence.

The mechanism presented here for explaining the equatorward expansion of the NASH southern boundary has not been previously reported in literature. This work demonstrates that, in the case of strong equatorial incurring South American cold surges, the impacts can extend well into the Northern Hemisphere subtropics if the upper level wind conditions in the Southern Hemisphere are conducive for deep equatorial penetration of the planetary wave associated with the low-level cold surge. The mechanism for this phenomenon is as follows:

- Upper level tropical westerlies are required in the Southern Hemisphere over Amazonia to allow for deep tropical penetration of Southern Hemisphere midlatitude planetary waves.
- As an upper-level midlatitude wave pattern crosses the Andes a cold surge is induced that transports cold, dry air into the tropical South America.
- Cold surges lead to anomalous high pressure in the lower troposphere and anomalous low pressure in the middle to upper troposphere over Southern Hemisphere tropical South America. The former leads to a southerly advection of cold air into the Northern Hemisphere in the lower troposphere,

whereas the latter leads to a northerly return flow in the middle troposphere.

Together, they form an anomalous SMC with low-level flow into the Northern Hemisphere and mid tropospheric return flow back to the Southern Hemisphere.

- Concurrently with the formation of the SMC, the NASH southern boundary migrates equatorward in response to the increased tropical-subtropical geopotential height and subtropical divergence created by the return flow of the SMC.

The mechanism presented here is not the only mechanism responsible for southern boundary migration of the NASH, as previously described Northern Hemisphere variability could also have influence. It should also be noted that this interhemispheric pathway will, in all likelihood, impact other atmospheric phenomena aside from the NASH in the Northern Hemisphere tropics and subtropics and should be explored further. For future work, it is also important to determine if GCM's and weather models realistically produce the observed cross equatorial influence from South American cold surges, and how more realistic representations of these processes could contribute to more accurate weather forecasting and future climate projections over the North Atlantic.

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